

Neural contributions to flow experience during video game playing

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Video games are an exciting part of new media. Although game play has been intensively studied, the underlying neurobiology is still poorly understood. Flow theory is a well-established model developed to describe subjective game experience. In 13 healthy male subjects, we acquired fMRI data during free play of a video game and analyzed brain activity based on the game content. In accordance with flow theory, we extracted the following factors from the game content: (i) balance between ability and challenge; (ii) concentration and focus; (iii) direct feedback of action results; (iv) clear goals; and (v) control over the situation/activity. We suggest that flow is characterized by specific neural activation patterns and that the latter can be assessed—at least partially—by content factors contributing to the emergence of flow. Each of the content factors was characterized by specific and distinguishable brain activation patterns, encompassing reward-related midbrain structures, as well as cognitive and sensorimotor networks. The activation of sensory and motor networks in the conjunction analyses underpinned the central role of simulation for flow experience. Flow factors can be validated with functional brain imaging which can improve the understanding of human emotions and motivational processes during media entertainment.

Keywords: video game; virtual reality; flow; reward; striatum; motor system

INTRODUCTION

Video game play is an exciting and fast growing segment of new entertainment media. Recently, neuroimaging studies addressed the effects of virtual reality and video games on brain systems. Modern video games contain highly realistic simulations of virtual environments; it has been shown that these virtual worlds evoke a strong feeling of being a part of the simulated environment (virtual presence; Sanchez-Vives and Slater, 2005) and that this feeling is characterized by activation of dorsal and ventral visual stream, parietal, temporal, and premotor areas, along with brainstem and thalamus (Baumgartner *et al.*, 2008; Jäncke *et al.*, 2009). Analyzing the neural substrates of game play, a positron emission tomography (PET) study found a correlation between performance level in a violent video game and dopamine release in the ventral striatum (nucleus accumbens, NAc; Koeppe *et al.*, 1998). In a similar vein, Hoeft *et al.* (2008) reported an activation of nucleus accumbens during a non-violent video game as compared to a control task with similar stimulus material. Other studies support the role of the NAc for reward processing (Ikemoto and Panksepp,

1999) as part of the mesolimbic dopaminergic pathway (Peterson, 2005), revealing an influence of video games on the brain reward system. This is in line with findings from media research where it is well established that video game play is a rewarding activity (e.g. Vorderer, 2000; Klimmt, 2001). However, since they do not relate their findings to a specific game content, these studies cannot answer the question what factors make games enjoyable and rewarding. So far there are only very few studies linking brain activity to dimensions of game content or player's experience. Mathiak and Weber (2006) and Weber *et al.* (2006a) used a content-based event-related analysis to specifically investigate the neural correlates of circumscribed game events. They reported distributed network activity during violence but interestingly no increased activity of the reward system. A similar approach was applied by Klasen *et al.* (2008) who investigated brain activation in relation to the players' behavior and their subjective experience, revealing a correlation between reported game pleasure and motor activity to demanding game situations. However, no study has addressed the neural substrates of motivational or enjoyment factors in video games.

Csikszentmihályi's (2000) concept of flow is one of the most prominent theories describing subjective game experience (e.g. Holt and Mitterer, 2000; Johnson and Wiles, 2003; Sherry, 2004; Sweetser and Wyeth, 2005; Keller and Bless, 2008; Weber *et al.*, 2009b). Flow is considered a mental state

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of being completely absorbed by an activity, accompanied by positive feelings. Csíkszentmihályi (1988, 1990, 2000) described the flow as being associated with a number of factors, which can be itemized as follows:

- (1) balance between the ability of the person and the challenges of the task;
- (2) concentrating and focusing on the activity;
- (3) direct and unambiguous feedback of action results;
- (4) clear goals of the activity;
- (5) control over the activity;
- (6) the activity is autotelic (intrinsically rewarding);
- (7) loss of self-consciousness (loss of awareness of oneself as a social actor);
- (8) distorted sense of time;
- (9) merging of action and awareness (the awareness is only focused on the activity).

The combined appearance of the factors was used to characterize a state of intensive enjoyment termed 'flow.' There is a wide consensus that video game enjoyment can be described in terms of flow experience (see Weber *et al.*, 2009b, for a review). Therefore flow theory poses a theoretical framework for the investigation of neural systems underlying game enjoyment. The present study focuses on observable game events contributing to the aforementioned flow factors. Factors 1–5 can be objectively assessed since they describe the interaction of the person and the environment created by the task. In contrast, the Factors 6–9 characterize internal states of the person experiencing flow. Factors 1–5 can, therefore, be seen as characteristics of the activity (the player–game interaction), and aspects of their expression can be inferred by observing the game play. For instance, in a first person shooter (FPS) game challenges and abilities are most evidently reflected in successful or failing combat situations which also give immediate feedback on the player's actions. We assumed that success situations emphasize the player's ability to cope with the demands of the situation and thus are closely related to the concept of reward. Moreover, the level of concentration can be related to the immediateness of enemy contact; an increase in concentration and focus is supposed to be reflected in higher attentional demands of the player, but also in visual processing shifts. Lower focus phases with no immediate enemy contact are assumed to require primarily spatial orientation in search for enemies which would be reflected by activation in the dorsal stream, whereas high focus with immediate enemy contact is likely to foster object-oriented processing. The latter may also apply to the active initiation of new game events which we employed for defining moments of high game control. Therefore, these factors are supposed to give objective evidence for the current presence of flow. We argue that an objective coding system based on the observation of gaming behavior can—at least partially—capture the observable factors of flow.

Flow is a well-established but so far mainly a heuristic construct. Based on the aforementioned observable aspects,

we want to detect the underlying neural patterns. Therefore, we analyzed fMRI data that reflect fluctuations in local brain activity during game play. The expression of the flow factors was based on objective game content descriptions. Content analyses of video games have been very effective in gaining objective data on the player's in-game behavior (Weber *et al.*, 2009a). We argue that correlations between neural activity and flow constructs would underpin their psychological relevance. Moreover, it could inform on basic mechanisms supporting the flow preconditions. The flow factors were hypothesized to affect emotional and attentional processes, reflected particularly in affective, cognitive and sensorimotor networks. Moreover, the involvement of midbrain reward system structures was considered reflecting enjoyment and positive game experience.

Finally, we hypothesized that a shared network reflects a central mechanism supporting flow states or—more generally—motivational processes during violent game playing. Thus, neural correlates of the factors may share common networks as well.

MATERIALS AND METHODS

Subjects

Thirteen male German volunteers (age 18–26 years, median 23) were recruited on the basis of previous experience with video games (average 15.1 ± 9.0 h/week) with ads posted at the local university and in video game stores. Inclusion criteria were: age between 18 and 26 years, playing at least 5 h weekly of video games and right-handedness. Individuals with contraindication against MR investigations, as well as acute or anamnesis of major neurological, psychiatric or ophthalmologic disorders were excluded. Aspects of this data set have been reported in Mathiak and Weber (2006); the comparison of violent events with the non-violent baseline revealed activation of the cognitive subsection of the anterior cingulate cortex (ACC) and inhibition in affective structures including the amygdala. For the current study, we added and analyzed a new data set of content factors to the brain imaging data described in Mathiak and Weber (2006). The experiment was designed according to the Code of Ethics of the World Medical Association (Declaration of Helsinki, 1964), and the study protocol was approved by the local Ethics Committee.

Imaging paradigm

Each volunteer played five preselected rounds of the FPS game 'Tactical Ops: Assault on Terror' (Infogrames Europe, Villeurbanne, France). In this game, the player together with simulated comrades (bots) fights against another group of bots in different scenarios termed 'maps', such as a castle or a desert town. The game is played from the first person perspective, meaning that the player experiences the action through the eyes of the virtual character which he controls. If a player is (virtually) killed before the round is over, he can observe the further game play from a viewer

perspective (ghost or dead mode), but has no opportunity to interact with other players until the next round.

For the purpose of this study, we selected the single player mode. Hereby, the player controls his virtual character while all other characters are controlled by the computer. Every map was played for at least 12 min. Sound and game screen were presented by MR compatible headphones and video screen, respectively, and the game was controlled by an MR compatible response device. Before the actual measurements, the participants were given time to practice until they felt comfortable with the setup. During each session, 12 min of brain activity were obtained by means of fMRI. The video display of the game play with the audio track was recorded for content analysis offline. fMRI was conducted at 3T (Magnetom TRIO, Siemens, Erlangen, Germany) by means of triple-echo single-shot echo-planar imaging [EPI; echo times (TE) = 23, 40 and 62 ms; 64×48 matrix with $4 \times 4\text{-mm}^2$ resolution; 4-mm slice thickness plus 1-mm gap] with dynamic distortion correction (Weiskopf *et al.*, 2005) and dephasing compensation (Mathiak *et al.*, 2004). Twenty-four oblique–transverse slices obtained whole brain coverage with repetition time (TR) = 2.25 s (330 volumes per session). Anatomical data were acquired from each participant before the functional sessions (T1-weighted 3D-MPRAGE, $256 \times 224 \times 160$ matrix with 1-mm isotropic voxels).

Content analysis

We developed a content coding system which allowed for a reliable and objective description of game events and the player's actions (compare Mathiak and Weber, 2006; Weber *et al.*, 2006b). All recorded and digitized videos of the subjects' game play were analyzed and defined game phases and events were noted with 100-ms time resolution. The time-based content analysis was performed by two independent coders and one supervisor. The coders received a coding training of ~16 h based on videos not used in the study. Cohen's κ (Krippendorff, 1980) was used as a measure for intercoder reliability. The coding procedure yielded an overall reliability of 0.85.

Aspects of five factors of flow according to Csíkszentmihályi (1988, 1990, 2000) were analyzed:

(1) Essential for the emergence of flow is the 'balance between ability and challenge' of the game play situation. 'When a person is bombarded with demands which he or she feels unable to meet, a state of anxiety ensues. [...] Flow is experienced when people perceive opportunities for action as being evenly matched by their capabilities. If, however, skills are greater than the opportunities for using them, boredom will follow' (Csíkszentmihályi, 2000, p. 50). A balance between the player's ability and the game challenge was assumed to be given in moments of success, i.e. during virtual killing, whereas this balance was absent in moments of failure (virtual dying of the player) when the player's abilities did not match the demands of the situation. We, therefore,

directly compared these success (killing) and failure (being killed) events. This comparison, moreover, eliminated the confounding variable of violence.

(2) An enjoyable activity asks for high 'concentration and focus', demanding all attention resources of the acting person. 'Perhaps the most universal of these [*characteristics of flow, author's note*] is the focused concentration people report whenever an activity is deeply enjoyable' (Csíkszentmihályi, 1988, p. 32). The dimension of focus was determined based on the game play phases in three levels: low focus was assumed to be given during game play encompassing waiting time between the rounds, while using the equipment menu, and in phases where no opponents could be seen or heard. Medium focus was given during potential danger phases (opponents visible or audible), and high focus was given during phases of active fighting.

(3) An unambiguous and 'direct feedback' of action results is crucial for the self-evaluation of the player's abilities and therefore a necessary precondition for flow experience. 'Another quality of the flow experience is that it usually [...] provides clear, unambiguous feedback to a person's actions' (Csíkszentmihályi, 2000, p. 46). Here we compared different instances of success events. High feedback was coded if the player further interacted with the dead body of the victim after the kill, whereas low feedback was coded when the latter was not observable. Success events were only considered if they ended the combat situation and the player did not have to subsequently face other opponents.

(4) Flow experience is committed to the presence of a 'Clear goal'. 'For this to happen [*emergence of flow, author's note*], however, the activity must have relatively clear goals [...]. It is difficult to become immersed in an activity in which one doesn't know what needs to be done' (Csíkszentmihályi, 1988, p. 32). Game phases without any visible or audible enemy contact were characterized by explorative player's behavior. Longer stays in these phases can be considered as lack of goal. We defined time epochs of >10 s in exploratory phases as absence of clear goal, whereas the first 10 s in these phases were considered as higher in Clear goal.

(5) 'Control' over the exerted activity is another important aspect for flow. 'Still another characteristic of a person in flow is that he is in control of his actions and of the environment' (Csíkszentmihályi, 2000, p. 44). This concerns the player's subjective feeling of control, but also the transition of the player's intentions into game actions (Pagulayan *et al.*, 2003). Active initiation of new game content by the player (starting/closing equipment menu; approaching/escaping from enemies; start/stop of use of weapon; killing an enemy) reflected high game control. Here the player influenced the course of the game by transforming his intentions into game actions. To reveal the specific neural correlates, the respective events were compared to the other phases of active game play.

It needs to be emphasized that these heuristic operationalizations neither exhaustively assess all flow factors nor necessarily reflect the state of flow. The observed phases merely are periods during which the probability for the emergence of flow is increased compared to random time points. To provide further evidence for the relation between the categories and flow experience, we conducted an explorative control study. Therefore 15 subjects not included in the fMRI study were assessed in a retrospective Think Aloud design (van Someren *et al.*, 1994). While they watched videos of the game sessions they had played immediately before, the players were asked about their experience during the game play. We noted time points of comments that indicated positive game or flow experiences. We observed an increased probability of the respective comments during success as compared to failure events [number of events $n=65$, relative risk $\beta=1.80$, 95% confidence interval (95% CI) = (1.54–2.06) in a binominal model], during high as compared to low concentration and focus [$n=87$, $\beta=3.19$ (2.68–3.70)], during high as compared to low feedback [$n=87$, $\beta=1.77$ (1.01–2.53)] as well as during high as compared to low Control [$n=87$, $\beta=3.19$ (2.68–3.70)], but not for the clear goal comparison [$n=29$, $\beta=0.82$ (0.47–1.18)]. Since the subjective comments underlie a self-reporting bias in flow studies (Weber *et al.*, 2009b), this study further concentrated on the objective neurophysiological measures.

fMRI Data Analysis

The reconstructed images underwent artifact reduction: construction of dynamic distortion maps from triple-echo EPI with alternating phase-encoding direction and subsequent matching and contrast-optimized combination of the three echoes (Mathiak *et al.*, 2004; Weiskopf *et al.*, 2005). Statistical parametric mapping was conducted following the standard SPM procedures with normalization into the Montreal Neurological Institute (MNI, Collins, 1994) template space of functional and anatomical data. fMRI data was smoothed with a 12-mm full-width at half-maximum Gaussian kernel and resampled to 2-mm³ voxel size. Data were time-synchronized to the recorded game play

videos and analyzed in an event-related fashion based on the aforementioned game play events as coded from the game content. A general linear model constructed from the coding phases convoluted with hemodynamic response function as independent variables; and random effect model for group analysis corrected for multiple testing across the entire brain volume. In addition to the maps reflecting significant responses to one of the analyzed factors each, we conducted conjunction analyses. The conjunction maps reflect neural networks that activated significantly during each of the investigated conditions, i.e. the global null-hypothesis that one or more of the predictors did not contribute to activity was rejected (Friston *et al.*, 2005). To correct for multiple comparisons we applied a threshold of $P < 0.05$ false discovery rate (FDR) corrected.

RESULTS

In this section, we first report the results for each of the flow factors separately. Subsequently, a conjunction analysis showing the common activations of the flow factors will be presented.

Balance between ability and challenge

Success and failure events served as a measure for the balance between player's skills and the demands of the situation. The analysis of the game content showed a total of 1064 success events (active kills), an average number of 82 events per subject. Failure was less frequent with an overall number of 338 events (26 per subject). A direct comparison of success and failure events revealed a stronger activation of midbrain structures, encompassing the head of caudate nucleus, nucleus accumbens, putamen (Figure 1A), cerebellum, thalamus, superior parietal cortex, motor and premotor areas (Figure 1B) for success and a stronger activation of the cuneus (Figure 1C) for failure events.

Concentration and focus

Low focus phases with no enemies visible or audible accounted for $79.3 \pm 7.4\%$ of the actively played game content; medium- and high-focus phases made up for $10.1 \pm 1.9\%$ and $10.6 \pm 2.5\%$ of the game content, respectively. The

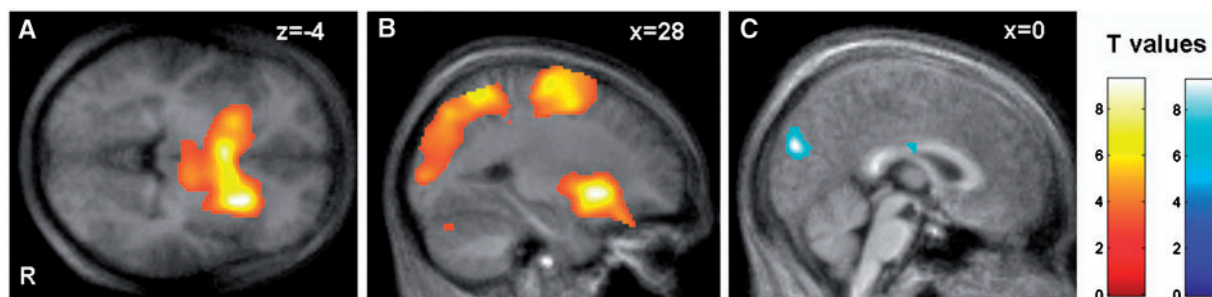


Fig. 1 Balance between ability and challenge. Activations to game success as compared to game failure. Success led to stronger activation of midbrain structures, cerebellum, thalamus, parietal and occipital areas, and premotor cortex (A and B) whereas failure was characterized by increased cuneus activity (C) ($P < 0.05$ FDR corrected).

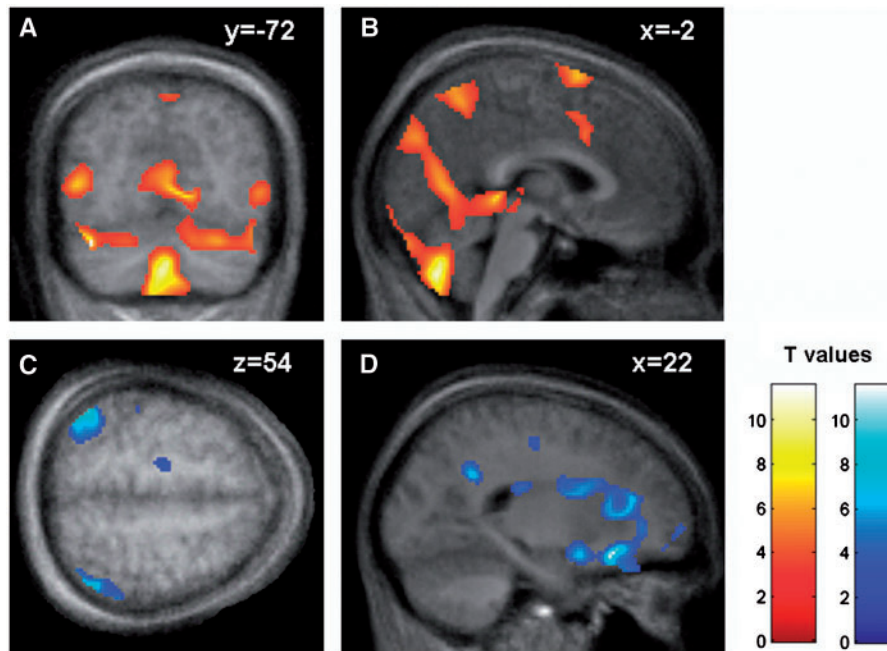


Fig. 2 Concentration and focus. Activations and deactivations to increasing focus level of the player. Higher focus led to cerebellar activation and activity increase in higher visual, parietal and premotor areas (A and B). Increasing focus was characterized by a deactivation of bilateral intraparietal sulcus (C), orbitofrontal cortex and rostral ACC (D) ($P < 0.05$ FDR corrected).

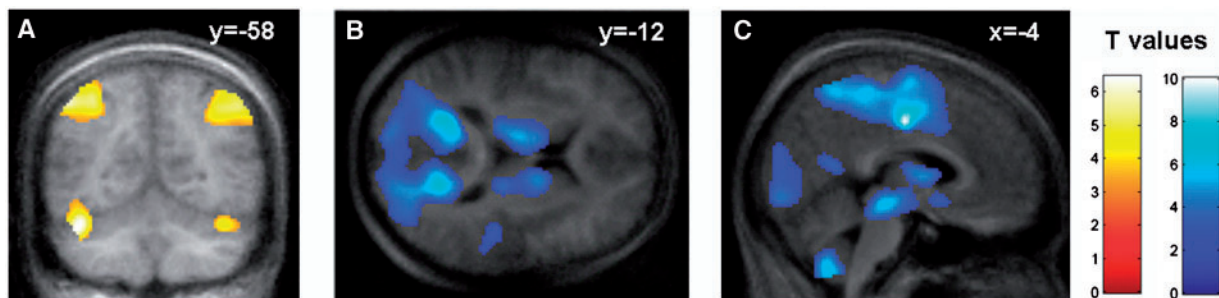


Fig. 3 Clear goals. Activations and deactivations during phases with goal-directed behavior. Bilateral IPS and fusiform face area are activated during phases with a clear goal (A). Precuneus (B) and dorsal ACC and thalamus (C) are deactivated ($P < 0.05$ FDR corrected).

passive (dead) phases were not taken into account. Increase of the player's focus was characterized by an increase of activation in the cerebellum and the visual system (Figure 2A), in the precuneus and premotor areas (Figure 2B) as well as by a decrease of activation in bilateral intraparietal sulcus (IPS, Figure 2C) and the orbitofrontal cortex (OFC) and the rostral part of the ACC (Figure 2D).

Direct feedback of action results

A further analysis concerned the role of clear feedback on success events. Clear feedback on the kill was given in 49 out of 1064 active kills. The analysis of the fMRI data revealed no significant effects at the predefined threshold of $P < 0.05$ (FDR corrected). Even at a descriptive threshold of $P < 0.001$ (uncorrected) no corresponding activation patterns could be

detected. Therefore this factor was not further considered in the conjunction analyses.

Clear goals

Safe game play phases without enemy contact made up for $60.8 \pm 7.7\%$ of the active game phases. Phases with clear goal as compared to the ongoing exploratory phase (>10 s) were characterized by an activation of bilateral IPS and fusiform face area (FFA) (Figure 3A) as well as decreased activation of the dorsal ACC (Figure 3B) and the precuneus (Figure 3C).

Control over the activity

We identified game events which were actively initiated by the player and defined them as moments of high game control. In total, the content analysis revealed 4047 events of

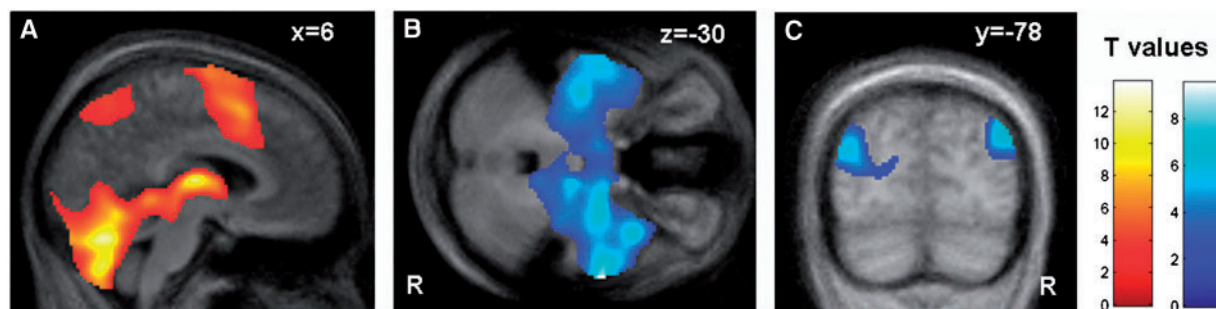


Fig. 4 Control over the activity. Activations and deactivations during active transitions. A corticothalamo-cerebellar network was activated during active transitions (A). Temporo-polar structures (B) were inhibited together with bilateral angular gyrus (C) ($P < 0.05$ FDR corrected).

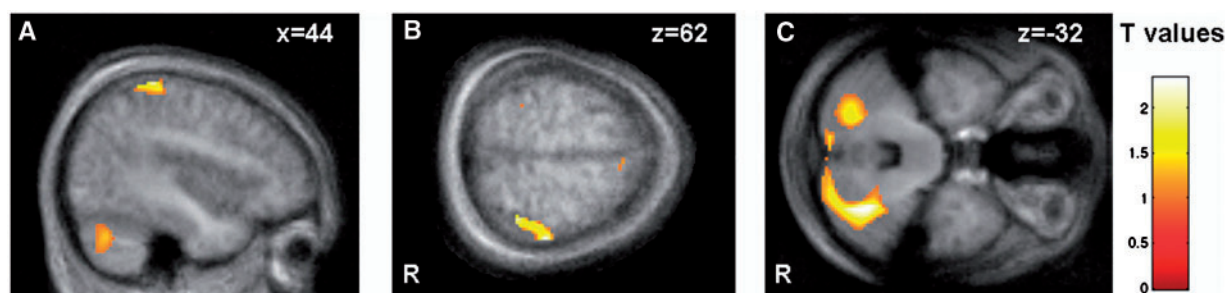


Fig. 5 Allover conjunction. Conjunction analysis for balance between ability and challenge \cap Focus \cap Clear goals \cap Control over the situation. A neocerebellar-somatosensory network is activated ($P < 0.05$ FDR corrected).

high control in the analyzed data, on average 311.3 events per subject. Considering the fMRI data, high control was characterized by activation in a network of visual, cerebellar, thalamic and motor-cortical regions (Figure 4A) and by a deactivation of bilateral temporal poles (TP) (Figure 4B) and bilateral angular gyrus (Figure 4C).

Conjunction across the flow factors

In order to test our hypothesis that the observable flow factors share common neural networks, we calculated conjunction analyses to reveal overlaps in the brain correlates. After exclusion of the direct feedback factor which was not associated with any significant effect, the analysis over the four block and event-related predictors showed a common neural substrate, encompassing neocerebellum and left primary and secondary somatosensory cortex (allover conjunction with FDR corrected $P < 0.05$; Figure 5A–C). However, clear goal was defined by phases or blocks rather than events and thus may reflect different neural dynamics. Thus selecting only factors that reflected events with significant responses, the event-related conjunction (balance between ability and challenge \cap concentration and focus \cap control) over the activity (FDR < 0.05) yielded complementary results: a motor simulation network emerged encompassing motor areas, thalamus and paleocerebellum (Figure 6A–C). The results of the conjunction analyses are depicted in Table 1.

DISCUSSION

We studied brain correlates of content factors contributing to the experience of flow in a video game. Since flow itself is a construct that cannot be assessed directly, we focused on observable aspects. A reliable and objective coding system extracted indicators for aspects of flow from player generated game content and served as a basis for the analysis of simultaneously acquired fMRI data. Neural correlates of five content factors were calculated revealing in four of them significant and meaningful neural networks. Moreover the conjunction of brain activity to the four factors revealed joint activity in somatosensory networks and the event-related conjunction showed common motor system activation. This finding underpins the importance of sensory-motor simulation to flow in video games.

The allover conjunction revealed the somatosensory network being jointly activated during flow-contributing factors (balance between ability and challenge \cap concentration and focusing \cap clear goals \cap control). Moreover, a network of motor areas reflected common activity patterns for three event-related flow factors (balance between ability and challenge \cap concentration and focusing \cap control). We assume that this sensorimotor activation reflects the simulation of physical activity in the game and that activation of this 'simulation network' contributes to the emergence of flow. Its components have been shown to be involved not only in the execution, but also in the simulation and imagination of

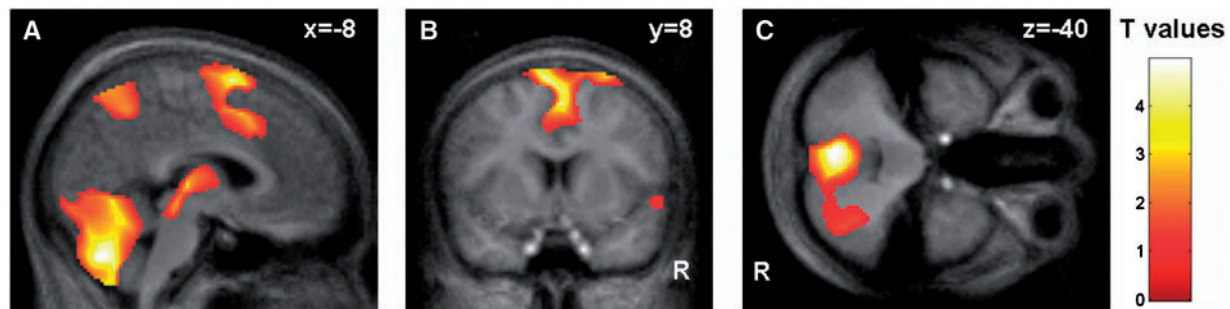


Fig. 6 Event-related conjunction. Conjunction analysis for balance between ability and challenge \cap Concentration and Focus \cap Control over the situation. Common activations reveal a motor simulation network including paleocerebellum, thalamus, hypothalamus and (pre-)motor areas ($P < 0.05$ FDR corrected).

Table 1 Activation clusters of the allover and event-related conjunction analyses show a somatosensory and a motor simulation network, respectively ($P < 0.05$, FDR corrected)

Anatomical region	Hemisphere	BA	MNI coordinates			<i>T</i>	Cluster size
			<i>X</i>	<i>Y</i>	<i>Z</i>		
Allover conjunction							
Neocerebellum	R/L	1, 2, 3, 7	34	−66	−32	2.33	1145
Postcentral gyrus/parietal lobe	R		52	−30	62	2.29	213
Neocerebellum	L		−14	−74	−48	1.75	75
Neocerebellum	L		−24	−74	−48	1.72	188
Event-related conjunction							
Cerebellum (vermis)	L/R	4, 6	−4	−72	−40	4.95	11 272
Precentral gyrus/medial frontal gyrus	L/R		−8	8	68	4.49	5579
Precuneus	R/L		10	−60	60	3.09	2026
Thalamus/midbrain	R/L		−4	−20	4	3.00	1497

motor actions without overt movements (Jeannerod and Frak, 1999; Jeannerod, 2001; Lotze and Halsband, 2006). Further evidence for this assumption comes from media research. Sherry *et al.* (2006) have shown that the opportunity of performing actions which are not possible in the real world is an important motivating factor for video game play. Video games deliver the opportunity of escaping from the surroundings of the real world and feeling like being a part of the virtual environment ('virtual presence'; Sheridan, 1992; Lee, 2004; Sanchez-Vives and Slater, 2005). We suggest that this feeling of involvement in the game and identification with the first person virtual character is reflected in the motor system activation, as a neural correlate of internally simulated physical motor activity. Thus it may reflect a state of being deeply immersed in the game which is characteristic for flow experience.

This model of motor representation of flow experience is in line with recent imaging studies on the neural basis of presence in a non-interactive virtual environment (Baumgartner *et al.*, 2008; Jäncke *et al.*, 2009). High vs low presence experience elicited patterns similar to those in our event-related conjunction encompassing somatosensory and premotor areas, superior parietal cortex, thalamus and

cerebellum. Furthermore, inferior parietal lobe downregulations were observed during the phases of high presence comparable to the focus condition in our study. Furthermore in parallel to the balance between the ability and challenge condition, the caudate nucleus is activated during high presence. Virtual presence and flow experience during video games are related concepts and may share neural correlates. Presence may facilitate the emergence of flow and correspond to the aspect of deep immersion which is characteristic for flow in games.

Separate flow factors revealed activations encompassing the reward system, thalamus, ACC, OFC, TP, motor system and IPS which can also be considered separately: the reward system activated in response to events characterized by a balance between the ability and challenge (virtual killing vs virtual dying). These activity changes in midbrain areas closely related to emotion and reward processing reflected a rewarding effect of moments when the player is able to master the challenges of the game. Primate studies have shown that putamen neurons track reward values and suggest a role of this structure in the guidance of goal-directed behavior based on action effort and reward size (Hori *et al.*, 2009) as well as on outcome probability (Haber and

Knutson, 2010). Effects of reward magnitude on neural activity have also been demonstrated in the caudate nucleus (Cromwell and Schultz, 2003), a structure involved in reward-based behavioral learning (O'Doherty *et al.*, 2004). Our findings are consistent with a recent imaging study by Rademacher *et al.* (2010) who found the thalamus as a neural substrate of reward consumption. Similarly, earlier functional imaging studies reported an influence of video games on midbrain structures (Koepp *et al.*, 1998; Hoeft *et al.*, 2008), and a recent structural MRI study revealed a correlation between volume of the striatum (caudate nucleus, nucleus accumbens, putamen) and the level of video game skill acquisition in an experimental training phase (Erickson *et al.*, 2010) which suggests a role of the striatum for the procedural learning of video game performance.

Failure events on the other hand—moments lacking the aforementioned balance—are characterized by enhanced activation in visual areas. A similar finding was reported by Regenbogen *et al.* (2009) as a result of observing virtual violence (not experiencing it in game play). Visual activation thus may not only reflect the lacking ability–challenge balance itself—enhanced visual activity may here indicate an effortful compensation of the latter—but also represent enhanced visual or multisensory attention toward a complex, attention-demanding stimulus. Since the video game used in our study switches instantly to the ghost (i.e. observer) mode when the player is virtually killed, events and results in both studies are comparable. Taken together, the brain correlates of the factor balance between ability and challenge show a simultaneous activation of reward system structures and a motor network consisting of cerebellum and premotor areas.

The involvement of the reward-motor loop is relevant to the recent theoretical approach of flow by Weber *et al.* (2009b). The authors posit flow as a discrete, energetically optimized state characterized by a cognitive synchronization of reward and attention brain networks, especially alerting and orienting networks as described by Fan *et al.* (2005). The neural correlates of the factor Balance of success and failure, however, show only a partial overlap with the alerting network (thalamus), which may be due to a high attention load also in failure situations. Nevertheless, the results provide evidence for a synchronization of reward structures with task-relevant cortical and cerebellar areas, underpinning the notion that flow experience cannot be reduced to activity of the reward system.

An increase in the player's focus is accompanied by premotor and paleocerebellar activation and activity increase in higher visual areas and by a deactivation of the rostral ACC, OFC and the IPS. The IPS has been shown to be involved in visuospatial working memory (Todd and Marois, 2004) and is considered part of a network for allocation of visuospatial attention (Corbetta *et al.*, 2002). Thus, the activation pattern may indicate that increasing focus shifts attention away from spatial orientation to object oriented processing. Moreover, we found BOLD response changes in the visual system, the

rostral ACC and the OFC as player's focus increased, reflecting an increase in attention and a suppression of distracting and non-task relevant emotions (Mathiak and Weber, 2006), whereas the deactivation of OFC may reflect a suppression of empathy in the first-person shooter game (Eslinger, 1998; Carrington and Bailey, 2009). These changes in the emotional state are necessary for the player to shift the focus of attention toward task-relevant game features in order to increase his performance. It remains open whether the neurophysiological responses to the observation or execution of virtual and real violent acts differ. Indeed, a recent investigation on a virtual version of the Milgram Experiment suggests a lack of activation in empathy-related networks in virtual settings. In this experiment, the subject is instructed to apply 'pain stimulation' to a virtual character as punishment for task failure. Although behavioral measures and physiological parameters indicate distress and negative feelings of the subject during this task (Slater *et al.*, 2006), no involvement of networks underlying empathy or affect emerged (Cheetham *et al.*, 2009). This is consistent with the view that empathic feelings toward other characters are even actively suppressed in the virtual environment of a violent game (also compare Mathiak and Weber, 2006). In a similar vein, real and virtual violence may evoke distinct neural patterns unaffected by a history of regular violent video game playing (Regenbogen *et al.*, 2009).

Goal-directed behavior was characterized by a decreased activity in precuneus and the cognitive subdivision of the ACC (Bush *et al.*, 2000) and by an increase of activity in the bilateral IPS and the right FFA. The FFA, an area prominently involved in the processing of faces (Kanwisher and Yovel, 2006), has also been shown to be active during 'expert distinctions', i.e. fine distinctions of well-known objects (Gauthier *et al.*, 2000). The stronger activity in this area in clear goal phases as compared to phases without a clear goal together with a deactivation of dorsal ACC and precuneus can reflect the shift from navigation in a well-known environment to enhanced conscious information processing in search for the next action (Vogt and Laureys, 2005). Thus, lack of a goal seems to animate the player to actively initiate new game content. Admittedly the factor clear goal—in our operationalization—failed to elicit more comments on flow-like experience and may also capture changes in attention and emotion not necessarily related to flow experience. Therefore the event-related conjunction (balance between ability and challenge, concentration and focus, and control over the situation) may be the most adequate depiction of the shared neural network underlying the flow factors as assessed in this study.

Although we did not measure the more subjective components of flow experience (Factors 6–9, see Introduction section) directly, the reported neurophysiological patterns underlying the other factors suggest their relevance. These states were not assessed by objective measures and brain patterns do not allow for confirmative conclusions.

Nevertheless, their presence may be hypothesized based on neural correlates reflecting previously detected psychological functions:

(6) 'A [...] characteristic of the flow experience is its 'autotelic' nature. In other words, it appears to need no goals or rewards external to itself' (Csíkszentmihályi, 2000, p. 47). All participants in our study reported to be regular players of the same game genre used in this study. Since there is no external reward in their everyday play, we can assume that the game play itself is the reward. During moments of balance between ability and challenge we observe a stronger activation of midbrain structures than during the absence of this balance, but moreover activity in motor systems is present not only during success but also during moments of high focus and high game control. As already stated above, we believe these to be correlates of simulated activities indicating highly immersive player states characterizing flow experience.

(7) 'A [...] characteristic of flow experiences has been variously described as 'loss of ego,' 'self-forgetfulness,' 'loss of self-consciousness,' and even 'transcendence of individuality' [...] (Csíkszentmihályi, 2000, p. 42). Loss of self-consciousness may be reflected in the loss of conscious perception as reflected in the IPS inhibition during increased focus. In how far this loss of conscious perception is also bound to a loss of self-consciousness is not clearly decipherable from the present data. A possible target structure for this is the temporoparietal junction including the angular gyrus, a region which is associated with embodiment (Arzy *et al.*, 2006) as well as with out-of-body experiences (Blanke *et al.*, 2005). The deactivation of the angular gyrus as observed during moments of high control is in agreement with the assumption of a change in conscious body perception.

(8) 'Another common feature of flow experiences is a "distorted" sense of time' (Csíkszentmihályi, 1988, p. 33). The cerebellum plays an important role in subjective time perception (Ivry and Fiez, 2000) and is involved in the processing of several of the flow factors. This activation pattern was particularly evident in the all-over conjunction analysis. Moreover, the IPS contributed to concentrating and focusing as well as to clear goals. Altered sense of time may be reflected in functional changes of cerebellum, IPS and prefrontal cortex (Mathiak *et al.*, 2002, 2004). Changes in time perception accompany the immersive player state and this co-occurrence may be reflected by the neocerebellar and IPS signal changes to the flow factors.

(9) 'Perhaps the clearest sign of flow is the merging of action and awareness' (Csíkszentmihályi, 2000, p. 38). Action awareness merging (the awareness is only focused on the activity) can be most readily associated with the visual system where the signal is increased if fMRI activity is associated with the conscious perception in the specific domain. A good example is the enhanced visual activity to the failure events. In addition, the suppression of non-task

relevant information as shown by the factor concentrating and focusing is indicating a merging of action and awareness.

We conclude that neural contributions to flow experience can be identified and that the content of flow factors was reflected in brain network activity patterns. Four of the factors—balance between ability and challenge, concentration and focus, clear goals and control over the activity—affected common networks. However, the remaining factor direct feedback failed to do so, although the behavioral study indicated its importance for flow experience. Conceivably, this predictor suffered from a lack of power since the number of active kills was not only subdivided in high and low feedback events but also omitted all kills in an ongoing fight. Furthermore, the distinction between high- and low-feedback events may not have been as evident to the player as it was to the coder. The structure of FPS games is in many ways constantly giving feedback via life points, tactical maps, and clearly visible kills. The coding system may thus have captured primarily attention to the kill and not the amount of direct feedback.

Limitations

The presented study investigated neural contributions to flow experience based on reliable and objective game content measures. However, flow is a highly subjective experience, and the actual emergence of flow experience was not assessed in this fMRI investigation. Instead, we investigated situations with an enhanced probability of flow experience. Obviously, this is not equivalent to measuring flow experiences directly. A similar limitation may have been the definition of the flow factors which were defined based on face validity of the game content. Preconditions or factors of flow are often not consciously processed and thus self-reports may only partially reveal them (Weber *et al.*, 2009b). Although self-report measures on flow experience have various limitations (Finneran and Zhang, 2003), we employed the latter in a control study to explore whether the coded phases and events were characterized by an increased probability of reported flow experience. These ratings cannot be assessed directly during the fMRI experiment without interfering with the subjective experience. Therefore, we consider the emergence of statistical significant activation patterns of meaningful networks an additional support for the validity of the constructs for flow.

CONCLUSION

We showed that aspects of the neural correlates of flow can be captured by brain imaging. We demonstrated an influence of flow on midbrain reward structures and on a complex network of sensorimotor, cognitive and emotional brain circuits. Remarkably, sensory-motor network activity appears to contribute to flow even in virtual reality.

Conflict of Interest

None declared.

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